

11/01/00

11-02-00

26 U.S. PTO  
99/704086

11/01/00

Please type a plus sign (+) inside this box →

PTO/SB/05 (7/98)  
Approved for use through 09/30/2000. OMB 0651-9032  
Patent and Trademark Office: U.S. DEPARTMENT OF COMMERCE

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

**UTILITY  
PATENT APPLICATION  
TRANSMITTAL**

**TRANSMITTAL**  
(Only for new nonprovisional applications under 37 C.F.R. § 1.53(b))

Attorney Docket No.		NC17173
First Inventor or Application Identifier		Venkatesh Vadde
Title	Partial Response Signaling for Orthogonal Frequency Division Multiplexing	
Express Mail Label No.		EL620282797US

## APPLICATION ELEMENTS

**APPLICATION ELEMENTS**  
See MPEP chapter 600 concerning utility patent application contents.

**ADDRESS TO:** Assistant Commissioner for Patents  
Box Patent Application  
Washington, DC 20231

1. ☒ \* Fee Transmittal Form (e.g., PTO/SB/17)  
(Submit an original and a duplicate for fee processing)
2. ☒ Specification [Total Pages 17]  
(preferred arrangement set forth below)
- Descriptive title of the Invention
  - Cross References to Related Applications
  - Statement Regarding Fed sponsored R & D
  - Reference to Microfiche Appendix
  - Background of the Invention
  - Brief Summary of the Invention
  - Brief Description of the Drawings (if filed)
  - Detailed Description
  - Claim(s)
  - Abstract of the Disclosure
3. ☒ Drawing(s) (35 U.S.C. 113) [Total Sheets 4]
4. Oath or Declaration [Total Pages ]
- a. ☒ Newly executed (original or copy)
  - b. ☐ Copy from a prior application (37 C.F.R. § 1.63  
(for continuation/divisional with Box 16 completed)
    - i. ☐ DELETION OF INVENTOR(S)  
Signed statement attached deleting  
inventor(s) named in the prior application  
see 37 C.F.R. §§ 1.63(d)(2) and 1.33(b)

5. ☐ Microfiche Computer Program (*Appendix*)
6. Nucleotide and/or Amino Acid Sequence Submission  
(*if applicable, all necessary*)
  - a. ☐ Computer Readable Copy
  - b. ☐ Paper Copy (identical to computer copy)
  - c. ☐ Statement verifying identity of above copies

## ACCOMPANYING APPLICATION PARTS

7. ☒ Assignment Papers (cover sheet & document(s))
8. ☐ 37 C.F.R. §3.73(b) Statement ☐ Power of Attorney  
(when there is an assignee)
9. ☐ English Translation Document (if applicable)
10. ☐ Information Disclosure Statement (IDS)/PTO-1449 ☐ Copies of IDS Citations
11. ☐ Preliminary Amendment
12. ☒ Return Receipt Postcard (MPEP 503)  
(Should be specifically itemized)
13. ☐ \* Small Entity Statement(s) ☐ Statement filed in prior application, Status still proper and desired  
(PTO/SB/09-12)
14. ☐ Certified Copy of Priority Document(s)  
(if foreign priority is claimed)
15. ☐ Other: .....

**\* NOTE FOR ITEMS 1 & 13: IN ORDER TO BE ENTITLED TO PAY SMALL ENTITY FEES, A SMALL ENTITY STATEMENT IS REQUIRED (37 C.F.R. § 1.27), EXCEPT IF ONE FILED IN A PRIOR APPLICATION IS RELIED UPON (37 C.F.R. § 1.28).**

16. If a **CONTINUING APPLICATION**, check appropriate box, and supply the requisite information below and in a preliminary amendment:  
☐ Continuation ☐ Divisional ☐ Continuation-in-part (CIP) of prior application No: \_\_\_\_\_  
 Prior application information: Examiner \_\_\_\_\_ Group / Art Unit: \_\_\_\_\_

Prior continuation information: Examiner Group / Art Unit:

**For CONTINUATION or DIVISIONAL APPS only:** The entire disclosure of the prior application, from which an oath or declaration is supplied under Box 4b, is considered a part of the disclosure of the accompanying continuation or divisional application and is hereby incorporated by reference. The incorporation can only be relied upon when a portion has been inadvertently omitted from the submitted application parts.

## 17. CORRESPONDENCE ADDRESS

- ☒ Customer Number or Bar Code Label  or ☐ Correspondence address below  
(Insert Customer No. or Attach bar code label here)

Name	Jubin Dana			26349	
	PATENT TRADEMARK OFFICE				
Address					
City		State		Zip Code	
Country		Telephone		Fax	

Name (Print/Type)	Jubin Dana	Registration No. (Attorney/Agent)	41.400
Signature		Date	Nov 1, 2000

Burden Hour Statement: This form is estimated to take 0.2 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, Patent and Trademark Office, Washington, DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, Box Patent Application, Washington, DC 20231

# FEE TRANSMITTAL for FY 2001

Patent fees are subject to annual revision.

## Complete if Known

Application Number  
Filing Date  
First Named Inventor  
Examiner Name  
Group Art Unit  
Attorney Docket No. NC17173

TOTAL AMOUNT OF PAYMENT (\$)

## METHOD OF PAYMENT

1. ☒ The Commissioner is hereby authorized to charge indicated fees and credit any overpayments to:
- Deposit Account Number: 50-0270  
Deposit Account Name: Nokia Inc.
- ☒ Charge Any Additional Fee Required Under 37 CFR 1.16 and 1.17  
☐ Applicant claims small entity status. See 37 CFR 1.27
2. ☐ Payment Enclosed:  
☐ Check ☐ Credit card ☐ Money Order ☐ Other

## FEE CALCULATION

### 1. BASIC FILING FEE

Large Entity		Small Entity		Fee Description	Fee Paid
Fee Code (\$)	Fee Code (\$)	Fee Code (\$)	Fee Code (\$)		
101	710	201	355	Utility filing fee	710.00
106	320	206	160	Design filing fee	
107	490	207	245	Plant filing fee	
108	710	208	355	Reissue filing fee	
114	150	214	75	Provisional filing fee	

SUBTOTAL (1) (\$ 710.00)

### 2. EXTRA CLAIM FEES

		Extra Claims		Fee from below	Fee Paid
Total Claims	10	-20** =	0	X	0.00
Independent Claims	3	-3** =	0	X	0.00
Multiple Dependent					

Large Entity		Small Entity		Fee Description	Fee Paid
Fee Code (\$)	Fee Code (\$)	Fee Code (\$)	Fee Code (\$)		
103	18	203	9	Claims in excess of 20	
102	80	202	40	Independent claims in excess of 3	
104	270	204	135	Multiple dependent claim, if not paid	
109	80	209	40	** Reissue independent claims over original patent	
110	18	210	9	** Reissue claims in excess of 20 and over original patent	

SUBTOTAL (2) (\$ 0.00)

\*\*for number previously paid, if greater; For Reissues, see above

## FEE CALCULATION (continued)

### 3. ADDITIONAL FEES

Large Entity		Small Entity		Fee Description	Fee Paid
Fee Code (\$)	Fee Code (\$)	Fee Code (\$)	Fee Code (\$)		
105	130	205	65	Surcharge - late filing fee or oath	
127	50	227	25	Surcharge - late provisional filing fee or cover sheet	
139	130	139	130	Non-English specification	
147	2,520	147	2,520	For filing a request for ex parte reexamination	
112	920*	112	920*	Requesting publication of SIR prior to Examiner action	
113	1,840*	113	1,840*	Requesting publication of SIR after Examiner action	
115	110	215	55	Extension for reply within first month	
116	390	216	195	Extension for reply within second month	
117	890	217	445	Extension for reply within third month	
118	1,390	218	695	Extension for reply within fourth month	
128	1,890	228	945	Extension for reply within fifth month	
119	310	219	155	Notice of Appeal	
120	310	220	155	Filing a brief in support of an appeal	
121	270	221	135	Request for oral hearing	
138	1,510	138	1,510	Petition to institute a public use proceeding	
140	110	240	55	Petition to revive - unavoidable	
141	1,240	241	620	Petition to revive - unintentional	
142	1,240	242	620	Utility issue fee (or reissue)	
143	440	243	220	Design issue fee	
144	600	244	300	Plant issue fee	
122	130	122	130	Petitions to the Commissioner	
123	50	123	50	Petitions related to provisional applications	
126	240	126	240	Submission of Information Disclosure Stmt	
581	40	581	40	Recording each patent assignment per property (times number of properties)	
146	710	246	355	Filing a submission after final rejection (37 CFR § 1.129(a))	
149	710	249	355	For each additional invention to be examined (37 CFR § 1.129(b))	
179	710	279	355	Request for Continued Examination (RCE)	
169	900	169	900	Request for expedited examination of a design application	

Other fee (specify)

\*Reduced by Basic Filing Fee Paid

SUBTOTAL (3) (\$)

## SUBMITTED BY

Name (Print/Type) Jubin Dana  
Signature

Registration No. 41,400  
(Attorney/Agent)

## Complete (if applicable)

Telephone 972-374-1285

Date Nov 1, 2000

WARNING: Information on this form may become public. Credit card information should not be included on this form. Provide credit card information and authorization on PTO-2038.

Burden Hour Statement: This form is estimated to take 0.2 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, Washington, DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, Washington, DC 20231.

## PARTIAL RESPONSE SIGNALING FOR ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

### CROSS-REFERENCE

5 This application claims the benefit of U.S. Provisional Application No.  
60/229,571, filed August 31, 2000.

### BACKGROUND

This invention relates to communication systems and, more specifically, to modulation techniques for communication systems.

10 Typical communication systems transmit information from one location or source to a second location or destination. The information travels from the source to the destination through a channel; this channel is typically a noisy channel. Thus, the channel introduces various forms of noise. The term "noise" is used herein to define various forms of signal corruption, such as interference, fading, attenuation, environmental impact, and electronic noise, that alter the characteristics of a signal as it travels through a channel. Accordingly, the signal that is transmitted through the channel and received at a receiver is a combination of the transmitted signal and the effects of noise introduced by the channel as a result of travelling through the channel.

20 In a cellular communications system, one type of noise is called "interference". More specifically, there are at least two forms of interference in communication systems: co-channel interference (CCI) and inter-symbol interference (ISI). CCI arises in communication systems due in part to the fact that there are several transmitters in communication with the same receiving unit. The signal from one transmitter can interfere with the signal from another transmitter. Each transmitter is an omni-directional transmitter. However, a signal being transmitted from one transmitter can take several paths as the signal travels from the transmitter to the receiver. This leads to ISI, a form of self interference. For example, in a cellular communication

25

system there are several mobile stations in communication with the same base station which often leads to CCI.

As indicated above, in a communication system information is transmitted through the channel from the source to the destination. The information is carried by a carrier signal that is modulated to contain or carry the information. Various forms of modulation are used for transmission of the information through the channel. Modulation is the process of varying the characteristic of a carrier according to an established standard or scheme; the carrier is prepared or "modulated" by the information to produce a "modulated" carrier signal that is transmitted by the source to the destination through the channel. For example, in a cellular communication system, modulation is the process of varying the characteristics of the electrical carrier as information is being transmitted. The most common types of modulation are Frequency Modulation (FM), Amplitude Modulation (AM), and Phase Modulation (PM).

One modulation technique currently used in the industry is called Orthogonal Frequency Division Multiplexing (OFDM). OFDM is one of the techniques for multicarrier modulation. Multicarrier modulation is a technique for modulating multiple carriers with different information, all of which are transmitted simultaneously or parallel in time. OFDM has high spectral efficiency as well as tolerance to multipath fading. As indicated above, transmitters are omni-directional and transmit in all directions. Thus, a signal emerging from a transmitter, or the source, can travel multiple paths to reach the receiver, or the destination. Accordingly, multipath fading occurs on a carrier signal's intensity, which results in alteration of the information being carried.

The efficiency of a system utilizing OFDM stems from the simultaneous or parallel transmission of several subcarriers in time. While this lowers the bit-rate on each of the subcarriers, it provides an "N"-fold increase in aggregate bit-rate, wherein "N" is the number of subcarriers. Additionally, because the low bit-rate signals hardly suffer any ISI and the

subcarriers are orthogonal, it is possible to demodulate the subcarriers independent of each other. A conventional OFDM system comprises a set of sub-symbols  $X[k]$  transmitted in time using an Inverse Fast Fourier Transform (IFFT). The time-domain baseband signal can be represented as:

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] \cdot \exp\left(\frac{j2\pi kn}{N}\right), n=0,1\dots N-1$$

10 Thus, the  $N$ -sample long transmitted OFDM symbol vector can be expressed as:

15 
$$x_N = \text{IFFT}\{X_N\}$$

where,  $x_N$  and  $X_N$  are the time and frequency domain symbol vectors, respectively.

In a typical OFDM system, binary symbols or bit streams are encoded in the form of complex valued numbers. The complex valued numbers are drawn from an  $M$ -ary alphabet. The complex valued numbers are then used to modulate a set of orthogonal sub-carriers to generate a time-domain signal using an Inverse Discrete Fourier Transform (IDFT). The resulting baseband signal, which is usually complex valued, is quadrature modulated on a Radio Frequency (RF) carrier and transmitted through an air interface channel. The transmitted signal is corrupted by channel noise and dispersion before being received.

There are several problems associated with systems that utilize OFDM modulation techniques. For example, the channel is subject to fading due to multipath and path loss. Additionally, the channel suffers from ISI which poses a problem at the receiver when data has to be detected. Furthermore, manufactures of devices that transmit and receive data are always faced with the challenge of increasing the amount of and the rate at

which information can be transmitted over a finite bandwidth while overcoming signal loss due to channel noise.

Therefore, what is needed is a system and method for minimizing the impact of ISI and fading on OFDM systems as well as enhancing the bit-rate.

## SUMMARY

A system and method are provided that minimize the impact of ISI and fading while allowing for an enhanced bit-rate. The system includes a transmitter for generating a signal and a cyclic prefix, wherein the transmitter suppresses a plurality of sub-symbols of the partial response signal to produce a truncated signal used to modulate a carrier signal to generate the signal, and a receiver in communication with the transmitter through a noisy channel for receiving a noisy signal and recovering the signal from the noisy signal by eliminating noise resulting from transmission through a noisy channel.

The method includes selecting a cyclic convolver having predefined values, applying the cyclic convolver to a signal to produce a partial response signal, wherein a portion of the partial response signal has near zero amplitude, dropping the portion of the partial response signal with near zero amplitude from the partial response signal to produce a truncated partial response signal, and appending a cyclic prefix at a leading edge of the truncated partial response signal.

An advantage of the present invention is that band-width gain is achieved without significant spectral expansion.

## BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram illustration of a system with a partial response technique of Orthogonal Frequency Division Multiplexing (OFDM) in accordance with the teachings of the present invention.

5 Fig. 2 is a graphical representation of an OFDM signal.

Fig. 3 is a graphical representation of a partial response OFDM signal altered by a preselected cyclic convolution polynomial.

Fig. 4 is a graphical representation of a partial response OFDM signal altered by a preselected cyclic convolution polynomial.

10 Fig. 5 is a flow chart of the process of generating the partial response OFDM signal using the system of Fig. 1.

## DETAILED DESCRIPTION

Referring now to Fig. 1, a communication system 10 is shown  
 15 having a transmitter 14, a channel 16, and a receiver 18, wherein the system 10 utilizes a Partial Response (PR)-Orthogonal Frequency Division Multiplexing (OFDM) signal modulation technique. The transmitter 14 includes a mapper 22, a cyclic convolver 24, a serial-to-parallel converter unit 26, an Inverse Fast Fourier Transform (IFFT) unit 28, a parallel-to-serial  
 20 converter unit 30, and prefix unit 32. The transmitter 14 transmits the information to the receiver 18 through the channel 16. The channel 16 is a noisy channel. The receiver 18 includes a serial-to-parallel converter unit 34, a Fast Fourier Transform (FFT) unit 36, a parallel-to-serial converter unit 38, a Maximum Likelihood (ML) estimator unit 40, and a demapper unit 42.

25 Information in the form of binary signals are received at the transmitter 14 and inputted to the mapper 22 for mapping to or encoding in the form of a set of complex numbers drawn from an M-ary alphabet to produce a complex signal, which is then used to modulate or prepare a carrier

signal for transmission as discussed in detail below. The transmitter 14 transmits the carrier signal through the channel 16 to the receiver 18. As the carrier signal, which is a time based signal, travels through the channel 16, the channel 16 introduces noise to the carrier signal, such as  $x[n]$ , corresponding to a channel impulse response, such as  $h[n]$ , of the channel 16. The cyclic convolver unit 24 performs a cyclic convolution on the complex signal. Additionally, the prefix unit 24 appends a cyclic prefix (CP) at the leading edge or the beginning of the complex signal that also helps compensate for the effects of the channel 16 and helps suppress Inter-Symbol Interference (ISI) in each of the low bit-rate sub-channels of the PR-OFDM signal.

The CP ensures that when the channel 16 performs a convolution on each OFDM time-symbol the effect of the channel 16 can be eliminated at the receiver 18. In a partial response (PR) technique, in accordance with the teaching of the present invention, inter-subcarrier (i.e., inter-channel) interference (ICI) is generated and introduced in the frequency domain based signal so as to shorten the effective time-domain symbol. The generated ICI is introduced to the complex signal by the cyclic convolver unit 24, as indicated above. The cyclic convolver unit 24 introduces, based on the desired or generated ICI, systematic or known amounts of dispersion to produce a partial response signal. In the system 10, the frequency symbol  $X_N$  is subjected to a cyclic convolution by a known polynomial  $c_N$  of order  $M$ , which is defined as follows:

$$c_N = [c(0) \ c(1) \ \dots \ c(M-1) \ 0 \ 0 \ \dots 0]$$

The PR polynomial can be expressed as a zero-padded vector of length  $N$  with  $M$  non-zero terms. The resulting time-domain symbol vector can now be expressed as follows:

$$x_N = \text{IFFT}\{X_N \otimes c_N\}$$



where,  $\otimes$  denotes cyclic convolution performed by the cyclic convolution unit 24, which disperses the information in each frequency-domain sub-symbol over  $M$  successive sub-carriers. Accordingly, the receiver 18 requires a sequence-detection mechanism to unravel the input sub-symbols  $X_N$ , and this is performed by the ML detector unit 40. Additionally, the other outcome of the cyclic convolution with  $c_N$  is that the original time vector-symbol  $x_N$  now bears an amplitude envelope given by the following:

$$e_N = \text{IFFT}\{c_N\}$$

By appropriately choosing the polynomial vector  $c_N$ , the transmitter 14 can effectively suppress energy in parts of the OFDM time symbol-vector, thereby producing a PR-OFDM symbol. For example, consider the set of polynomials obtained from the coefficients of powers of  $r$  in  $p(r)$ , where:

$$p(r) = (1-r)^m; \quad m = 1, 2, \dots$$

The envelope vector resulting from such a polynomial has a null at each of its extremities. Consequently, the energy at the extremities or the tails of the envelope of the time-domain symbol vector is effectively suppressed and can be dropped. Thus, the cyclic convolver unit 24 generates a partial response signal with near zero energy at the extremities in the time domain.

The partial response signal, which is a frequency domain based signal, is then received by the serial-to-parallel unit 26. The serial-to-parallel unit 26 converts the partial response signal from serial to parallel signaling and passes the parallel partial response signal to the IFFT unit 28. The IFFT unit 28 performs a modulation that is a transformation on the parallel partial response signal to generate real and imaginary components in the time

domain. The transformed parallel partial response signal is derived from the partial response signal. The real and imaginary components of the transformed parallel partial response signal are received by the parallel-to-serial unit 30, which converts to serial signaling to produce a transformed partial response signal that is ready for transmission.

Referring now to Figs. 2, 3, and 4, the effect of the partial response generating polynomial on the time-domain symbol vector is illustrated on a 64-sample time-symbol. Referring specifically to Fig. 2, a 64-sample time-symbol is shown in absolute value or magnitude only, which is drawn from a set of randomly picked Quadrature Phase Shift Keyed (QPSK) sub-symbols in the frequency domain. Although Fig. 2 illustrates QPSK sub-symbols, any constellation can be used for the partial response signal. In Figs. 3 and 4, the corresponding time-symbol magnitudes using a PR polynomial  $c$  of order  $M=2$  and  $M=4$ , respectively, are illustrated with several of the samples of the time-symbol suppressed near the ends. Dropping the samples near the ends results in virtually no performance loss because the energy at the tails of this time-symbol is very low. The label "dropping" is used herein to mean that the sub-symbols are not transmitted as part of the transmitted partial response signal. Accordingly, dropping or not transmitting the low-energy samples essentially enables compression of the signal in time, thereby achieving significant time or bandwidth gains. Reducing the time taken to transmit an OFDM time-symbol because of the PR effects can be construed as leading to extra bandwidth.

In one embodiment, the system 10 is an OFDM system using 64 sub-carriers. The PR polynomial orders from  $M=1$  to  $M=4$  are utilized in the system 10. For  $M=1, 2, 3$  and  $4$ ,  $d=12, 16, 24$  and  $32$  samples, respectively, (i.e.,  $6, 8, 12$ , and  $16$  samples from each extremity) are dropped. Therefore, in the absence of any other performance loss in BER or SNR the fraction of time saved in communicating an OFDM time-symbol is  $d/N$ . Consequently, the time saved is  $12/64, 16/64, 24/64$  and  $32/64$  or  $18.75\%, 25\%, 37.5\%$  and  $50\%$  for  $M=1, 2, 3$  and  $4$ , respectively. Accordingly, the time saved can be

used to transmit additional OFDM symbols and the corresponding bandwidth gain, which is measured as extra transmissions possible in a given amount of time, is 23%, 33%, 60% and 100%, for  $M=1, 2, 3$  and 4, respectively.

As indicated, the bandwidth gain is achieved with minimum spectral expansion, which is discussed in detail below. It will be apparent to those skilled in the art that the OFDM signal  $s_1(t)$  before insertion of the CP can be represented as follows:

$$s_1(t) = \sum_{k=-\infty}^{\infty} p_k \{t - kN \Delta T\} \quad (1)$$

where,  $N$  is the FFT-size,  $\Delta T = T/N$ , and  $p_k(t)$  is the  $k^{\text{th}}$  baseband OFDM symbol transmitted in  $[(k-1)T, kT]$ .

The  $n^{\text{th}}$  sample,  $s_1[n]$ , of the signal is equal to  $p_k[m]$ , the  $m^{\text{th}}$  sample of the pulse  $p_k(t)$ , where  $n = (m+kN)$ . In one embodiment of PR signaling,  $d$  sub-symbols, wherein  $d$  is even, at the extremities are dropped from each OFDM symbol because the magnitudes of the dropped sub-symbols are relatively insignificant; dropping the sub-symbols from the OFDM signal produces a PR-OFDM signal in the time domain. In an alternative embodiment of PR Signaling, the sub-symbols dropped can be in any part of the PR signal. The PR-OFDM time-based signal therefore comprises symbols with  $(N-d)$  samples each, where the  $k^{\text{th}}$  symbol contains a subset of samples from  $p_k(t)$ , specifically, the  $(d/2+1)^{\text{th}}$  to  $(N-d/2)^{\text{th}}$  sample. The PR-OFDM signal  $s_2(t)$  can be expressed in terms of the pulse-train  $p_k(t)$  as follows:

$$s_2(t) = \sum_{k=-\infty}^{\infty} p'_k \{t - k(N-d)\Delta T\}$$

where, the pulses  $p'_k(t)$  and  $p_k(t)$  are related as,

$$p'_k(t) = p_k\left\{t + \left(\frac{d}{2} + 1\right)\Delta T\right\} \cdot \text{rect}\left\{\frac{t}{(N-d)\Delta T}\right\}$$

where,  $\text{rect}(t) = 1 \forall t \in [0, 1]$ , and 0 otherwise.

The power spectral density (PSD) of the pseudo random signal represented by equation (1) can be computed from the auto correlation function of  $s_1(t)$ . Clearly, the auto correlation of  $s_1(t)$  is confined to the interval  $[-N\Delta T, N\Delta T]$ . This follows from the confinement in time of  $p_k(t)$  itself to  $[0, N\Delta T]$ , and from the fact that different OFDM symbols are zero-mean as well as uncorrelated. Auto correlation of  $s_1(t)$  is the same as that of the ensemble of pulses  $p_k(t)$  i.e.,  $R_s(t) = R_p(t)$ . The pulses  $p'_k(t)$  are derived from  $p_k(t)$ , thus, it follows that:

$$R_{p'}(t) = R_p(t) \cdot \text{rect}\left\{\frac{t}{2(N-d)\Delta T}\right\}$$

Thus, the PSD  $S_{p'}(f)$  of the continuous-time PR-OFDM signal  $s_2(t)$  is related to the PSD  $S_p(f)$  of the regular OFDM signal  $s_1(t)$  in equation (1) as follows:

$$\begin{aligned} S_{p'}(f) &= FT\{R_{p'}(t)\} = FT\left\{R_p(t) \cdot \text{rect}\left(\frac{t}{2(N-d)\Delta T}\right)\right\} \\ &= (2(N-d)\Delta T) S_p(f) * \text{sinc}(2(N-d)f\Delta T) \\ &\propto S_p(f) * \text{sinc}(2(N-d)f\Delta T) \end{aligned} \tag{1.1}$$

where,  $*$  denotes convolution. For  $M=4$ , the value of  $d \approx N/2$ , implying the bandwidth increases by a factor  $\text{sinc}(fT)$ . The impact of this factor, in the

frequency domain, for the case  $M=4$  and the choice  $d=N/2$  is shown in Fig. 5 against the backdrop of the normal OFDM spectrum of Fig. 5. Accordingly, the spectral expansion is negligible compared to the large bandwidth gains possible through PR-OFDM.

5           The PR-OFDM signal has parts of the time-symbol suppressed. The cyclic convolution polynomial is selected so that the suppressed parts lie towards the extremities of the time-symbol, even though a polynomial could be selected to suppress any portion of the OFDM, such as the middle portion. In the present embodiment, the suppression occurs at the extremities of the

10 time-symbol. With the extremities of the time domain symbol suppressed, a CP can be added without interference from the signal itself. The length of the CP to be appended is usually fixed as the maximum channel length,  $L$ , to be encountered. At the receiver 18, the CP bears all of the ISI and is simply dropped for detection purposes, as will be discussed in detail below. Thus, an

15 orthogonal choice of subcarriers with a CP provide a multicarrier technique free of ISI and inter-subcarrier (i.e., inter-channel) interference (ICI). The cyclic-prefix or CP by definition is chosen to be the last  $L$  samples of the symbol and is appended to the beginning. For PR-OFDM in our case, we will always use an order of PR polynomial such that the number of suppressed

20 sub-symbols satisfies  $d/2 > L$ . Thus, the CP will simply consist of  $L$  blank (i.e., all-zero) sub-symbols appended to the truncated symbol  $p'_k[n]$ . It is an added advantage therefore that the CP used in PR-OFDM can have little or no energy.

          The partial response signal is transmitted through the channel

25 and received at the receiver 18 as a transmitted partial response signal. The transmitted partial response signal is received at the serial-to-parallel unit 34 and converted to a parallel transmitted partial response signal and passed to the FFT unit 36. The FFT unit 36 performs the inverse transformation of the transformation performed by the IFFT unit 28 and, hence, transforms the

30 signal from a time domain based signal to a frequency domain based signal to produce a converted parallel transmitted partial response signal. The

converted parallel transmitted partial response signal is passed to the parallel-to-serial unit 38. The parallel-to-serial unit 38 changes the converted parallel transmitted partial response signal to a converted transmitted partial response signal. The converted transmitted partial response signal is passed to a maximum likelihood (ML) detector unit 40. The ML unit 40 unravels the converted transmitted partial response signal to produce or recover the complex-number based signal. The demapper unit 42 converts the complex-number based signal into a binary stream that is outputted from the receiver.

Referring now to Fig. 5, the process of generating a PR-OFDM signal begins at step 100. At step 110, a cyclic convolver is selected that reduces the extremity sub-symbols to near zero amplitude. At step 120, the cyclic convolver is applied to the signal to generate a convolved signal. At step 130, the signal is transformed from the frequency domain to the time domain. At step 140, the near zero amplitude sub-symbols of the convolved signal are dropped to produce a PR-OFDM signal. At step 150, a cyclic prefix is appended to the PR-OFDM signal and the process ends at step 160.

Although described in the context of particular embodiments, it will be apparent to those skilled in the art that a number of modifications to these teachings may occur. Thus, while the invention has been particularly shown and described with respect to one or more preferred embodiments thereof, it will be understood by those skilled in the art that certain modifications or changes, in form and shape, may be made therein without departing from the scope and spirit of the invention as set forth above and claimed hereafter.

## CLAIMS

What is claimed is:

1. A communication system comprising:

a transmitter for generating a signal, wherein the signal is generated from a partial response signal produced from mapping an input bit stream to a complex number domain and wherein the transmitter suppresses a plurality of sub-symbols of the partial response signal to produce a truncated signal used to modulate a carrier signal to generate the signal; and

a receiver in communication with the transmitter through a noisy channel for receiving a noisy signal, wherein the receiver recovers the signal from the noisy signal by eliminating noise resulting from transmission through a noisy channel.

2. The system of claim 1, wherein the transmitter comprises:

a mapping unit for mapping the input bit stream to a complex number domain;

a cyclic convolver unit coupled to the mapping unit for generating a partial response signal; and

a prefix unit for appending a cyclic prefix to a leading edge of the truncated signal.

3. The system of claim 2, further comprising a transform unit for converting the partial response signal to a time domain signal and suppressing the plurality of sub-symbols.

1 4. The system of claim 2, wherein the receiver comprises a  
2 detector unit for recovering the signal from the noisy signal.

1 5. The system of claim 2, wherein the suppressed plurality of sub-  
2 symbols are distributed evenly at the edges of the partial response signal.

1 6. A method for increasing bit-rate through effective bandwidth gain in a  
2 system utilizing an orthogonal frequency division multiplexing technique, the  
3 method comprising:

4 selecting a cyclic convolver having predefined values;

5 applying the cyclic convolver to a signal having a plurality of sub-  
6 symbols to produce a partial response signal having the plurality of sub-  
7 symbols, wherein the values of the cyclic convolver are selected such that a  
8 portion of the plurality of sub-symbols of the partial response signal are  
9 reduced to near zero amplitude;

10 dropping the portion of the plurality of sub-symbols with near zero  
11 amplitude from the partial response signal to produce a truncated partial  
12 response signal; and

13 appending a cyclic prefix at a leading edge of the truncated partial  
14 response signal.



1 7. The method of claim 6, further comprising:  
2 transforming the partial response signal using an inverse fast fourier  
3 transformation technique to produce a time based signal;  
4 transmitting the time based signal through a noisy channel to produce  
5 a noisy signal; and  
6 recovering the time based signal from the noisy signal at a receiver.

1 8. A system for delivering information from a source to a destination, the  
2 system comprising:  
3 means for converting the information to a frequency domain signal;  
4 means for transforming a frequency domain signal to a time domain  
5 signal, wherein the means for transforming is coupled to the means for  
6 converting and wherein the transformation results in a plurality of sub-symbols  
7 having near zero amplitude; and  
8 means for dropping the plurality of sub-symbols having near zero  
9 amplitude to produce a truncated time domain signal, wherein the means for  
10 dropping is coupled to the means for transforming.

9. The system of claims 8, further comprising:

means for delivering the truncated time domain signal from the source to the destination, wherein the means for delivering is coupled to the means for dropping; and

means for receiving the delivered truncated time domain signal, wherein the means for receiving is coupled to the means for delivering and wherein the means for receiving comprises:

means for recovering a received truncated time domain signal from the delivered truncated time domain signal, wherein the received truncated time domain signal represents the truncated time domain signal;

means for inserting a plurality of zero value samples in the received truncated time domain signal to produce a received time domain signal, wherein the means for inserting is coupled to the means for recovering and wherein the received time domain signal represents the time domain signal; and

means for transforming the received time domain signal to a received frequency domain signal, wherein the means for transforming the received time domain signal is coupled to the means for inserting and wherein the received frequency domain signal represents the frequency domain signal.

10. The system of claim 9, further comprising means for recovering a received information from the received frequency domain signal, wherein the means for recovering is coupled to the means for transforming the received time domain signal and wherein the received information represents the information.

## ABSTRACT

The system includes a transmitter for generating a signal and a cyclic prefix, wherein the transmitter suppresses a plurality of sub-symbols of the signal to produce a partial response signal. A portion of the partial response signal is dropped and the resulting truncated signal is used to modulate a carrier signal. The carrier signal is transmitted to the receiver through a noisy channel. The receiver receives a noisy signal and recovers the carrier signal and, hence, the partial response signal from the noisy signal. The method includes selecting a cyclic convolver having predefined values, applying the cyclic convolver to a signal to produce a partial response signal, dropping a plurality of sub-symbols of the partial response signal, appending a cyclic prefix at a leading edge of the truncated partial response signal, and transforming the truncated partial response signal with the cyclic prefix to produce a time base signal that is used to generate a modulated carrier signal that is ready for transmission.

NC/7173  
1 of 4

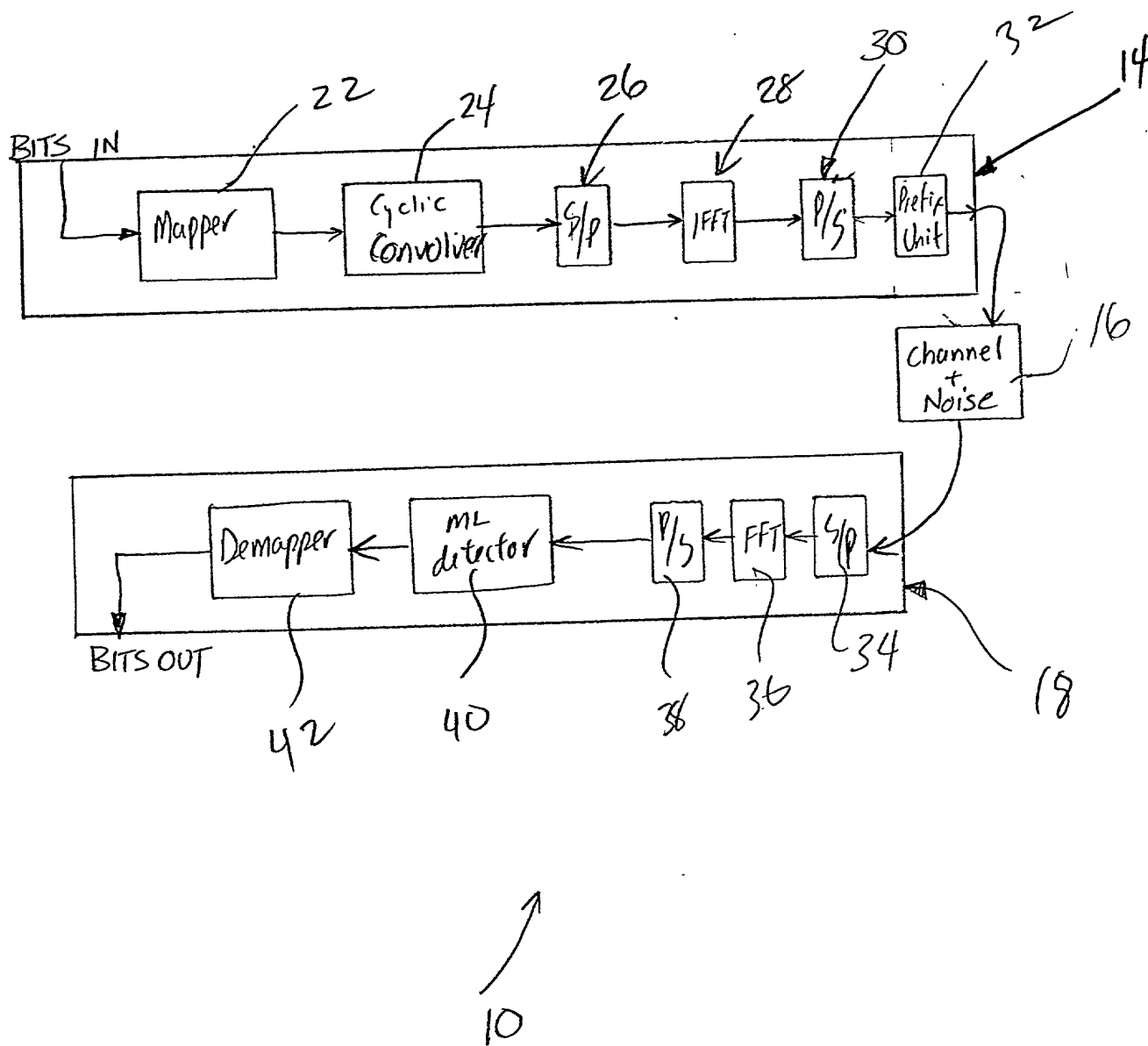


Fig. 1.

NC17173  
26.4

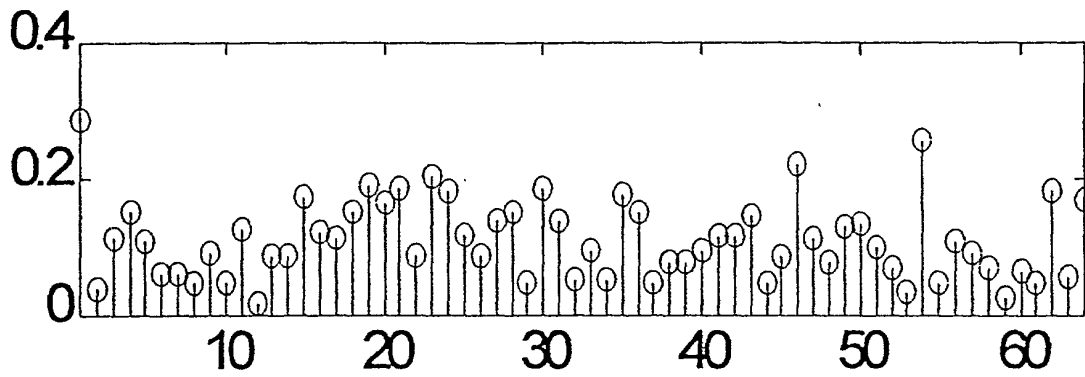


Fig. 2

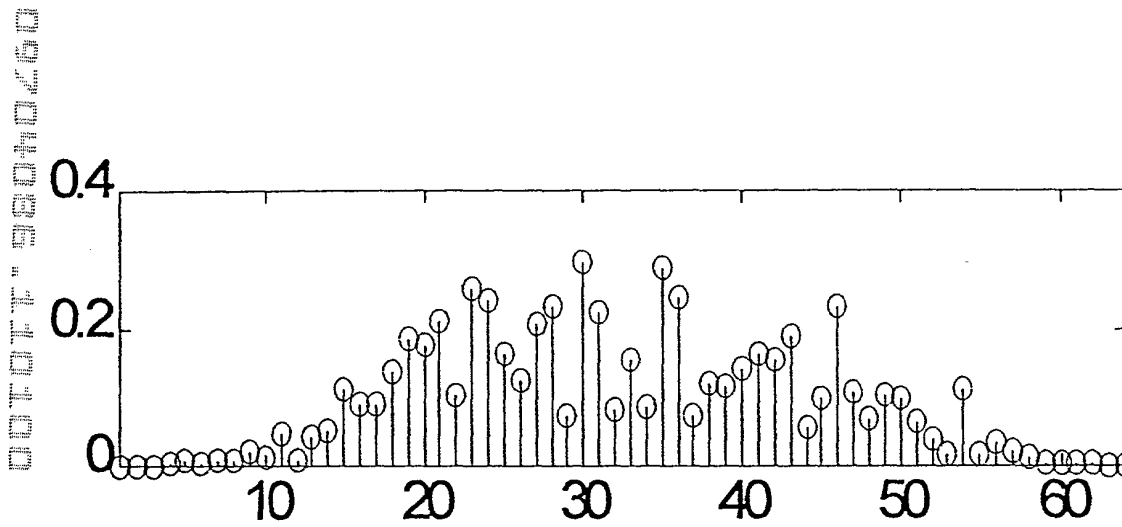


Fig. 3

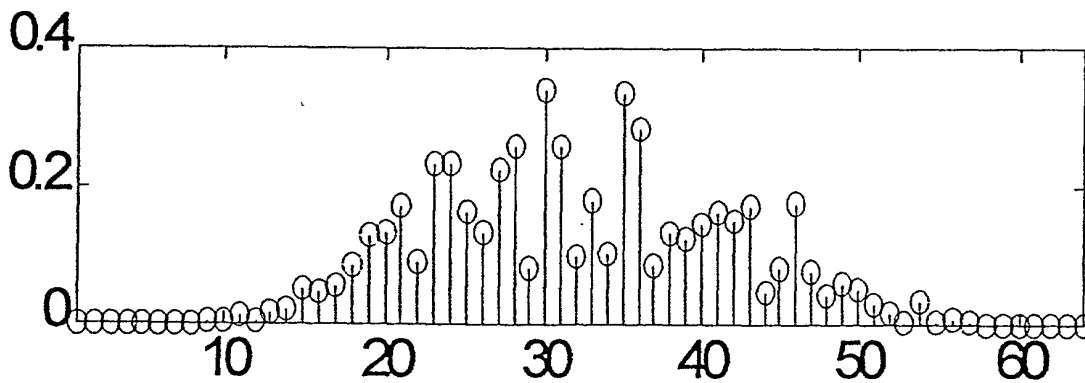


Fig. 4

NC 17173  
3 of 4

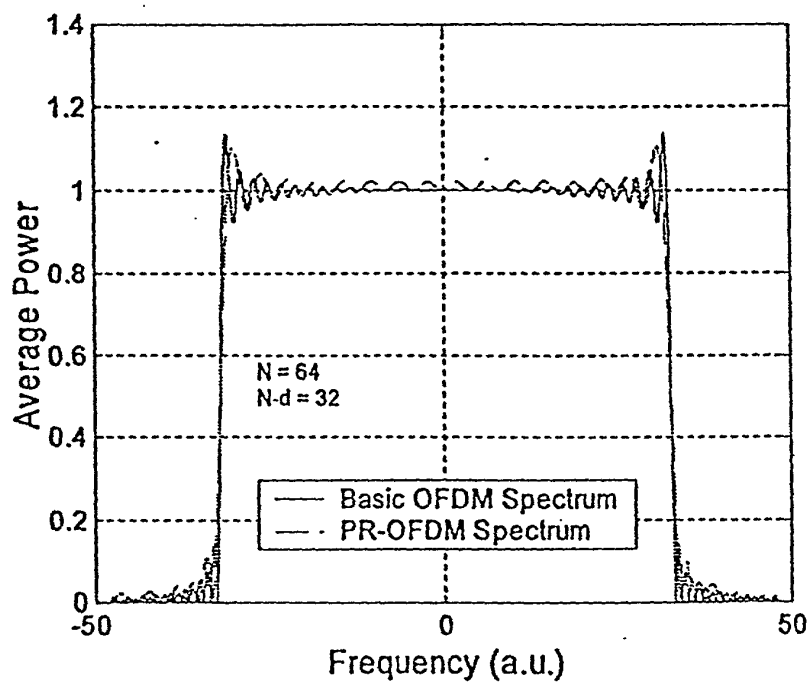


Fig. 5

NC17173  
4 of 4

START 100

SELECT A CYCLIC  
CONVOLVER 110

APPLY CYCLIC  
CONVOLVER TO  
THE SIGNAL 120

TRANSFORM SIGNAL  
FROM FREQUENCY  
DOMAIN TO TIME  
DOMAIN SIGNAL 130

DROP SUB-SYMBOL  
WITH NEAR  
ZERO AMPLITUDE 140

APPEND A  
CYCLIC PREFIX 150

END 160

Fig. 6

Please type a plus sign (+) inside this box → ☐

PTO/SB/01 (12-97)  
Approved for use through 9/30/00. OMB 0651-0032  
Patent and Trademark Office; U S DEPARTMENT OF COMMERCE

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

<b>DECLARATION FOR UTILITY OR DESIGN PATENT APPLICATION</b> <b>(37 CFR 1.63)</b>  <input type="checkbox"/> Declaration Submitted with Initial Filing      OR <input type="checkbox"/> Declaration Submitted after Initial Filing (surcharge (37 CFR 1.16 (e)) required)	<b>Attorney Docket Number</b>	NC17173
	<b>First Named Inventor</b>	Venkatesh Vadde
	<b>COMPLETE IF KNOWN</b>	
	<b>Application Number</b>	/
	<b>Filing Date</b>	
	<b>Group Art Unit</b>	
	<b>Examiner Name</b>	

**As a below named inventor, I hereby declare that:**

My residence, post office address, and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

**Partial Response Signaling for Orthogonal Frequency Division Multiplexing**

the specification of which (Title of the Invention)

☒ is attached hereto  
OR  
☐ was filed on (MM/DD/YYYY) [ ] as United States Application Number or PCT International Application Number [ ] and was amended on (MM/DD/YYYY) [ ] (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56.

I hereby claim foreign priority benefits under 35 U.S.C. 119(a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or of any PCT international application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application Number(s)	Country	Foreign Filing Date (MM/DD/YYYY)	Priority Not Claimed	Certified Copy Attached?	
				YES	NO
			<input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>

☐ Additional foreign application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto:

I hereby claim the benefit under 35 U.S.C. 119(e) of any United States provisional application(s) listed below.

Application Number(s)	Filing Date (MM/DD/YYYY)	<input type="checkbox"/> Additional provisional application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto.
60/221,571	August 31, 2000	

[Page 1 of 2]

Burden Hour Statement: This form is estimated to take 0.4 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, Patent and Trademark Office, Washington, DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, Washington, DC 20231.



Please type a plus sign (+) inside this box → ☐

PTO/SB/01 (12-97)  
Approved for use through 9/30/00. OMB 0651-0032

Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number

## DECLARATION — Utility or Design Patent Application

I hereby claim the benefit under 35 U.S.C. 120 of any United States application(s), or 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. 112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application.

U.S. Parent Application or PCT Parent Number	Parent Filing Date (MM/DD/YYYY)	Parent Patent Number (if applicable)

☐ Additional U.S. or PCT international application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto

As a named inventor, I hereby appoint the following registered practitioner(s) to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith: ☐ Customer Number  OR ☒ Registered practitioner(s) name/registration number listed below

Place Customer Number Bar Code Label here

Name	Registration Number	Name	Registration Number
Brian T. Rivers	41,270	Linda Beach	36,446
Jubin Dana	41,400	Milan Patel	41,242
Jerry Gruschke	42,588	Robert Rolnick	37,995
Allen Lineberry	44,873	Steven Shaw	39,368

☐ Additional registered practitioner(s) named on supplemental Registered Practitioner Information sheet PTO/SB/02C attached hereto.

Direct all correspondence to: ☐ Customer Number  OR ☒ Correspondence address below

Name	Jubin Dana				
Address	Nokia Inc MD 1-4-755				
Address	6000 Connection Drive				
City	Irving	State	TX	ZIP	75039
Country	USA	Telephone	972-374-1285	Fax	972-894-5619

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon

Name of Sole or First Inventor:		<input type="checkbox"/> A petition has been filed for this unsigned inventor			
Given Name (first and middle [if any])		Family Name or Surname			
Venkatesh		Vadde			
Inventor's Signature	<i>Venkatesh</i>			Date	Nov 1 2000
Residence: City	Irving	State	TX	Country	USA
				Citizenship	Indian
Post Office Address	852 Kinwest Pkwy, #219				
Post Office Address					
City	Irving	State	TX	ZIP	75063
				Country	USA

☐ Additional inventors are being named on the \_\_\_\_\_ supplemental Additional Inventor(s) sheet(s) PTO/SB/02A attached hereto